TEMPORAL CHARACTERIZATION OF ROCK DYNAMIC DESTRUCTION

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Abstract. Dynamic strength tests published in literature have been analysed by structural-temporal damage criteria. Parameter τ - incubation time - describing material stability behaviour under high-rate influences have been estimated for Kimachi sandstone, Inada granite and Tage tuff. Two types of dynamic tensile experiments have been used: split Hopkinson pressure bar and spalling. Purely dynamic effect of fracture delay have been observed in the case of Kimachi sandstone and discussed.

1 INTRODUCTION

Nowadays geoscience and mining industry problems require consideration of new physical effects for accurate modelling of flowing processes. Area of rock formation stability problems includes both long-lasting quasistatic processes and rapid influences. Last ones are related with effect of dynamic strength.

It was empirically observed that material under dynamic impulses is able to withstand stresses much bigger than its static strength in both compression and tension. Moreover increasing of loading rate leads to rising of maximum stress went through material at the moment of rupture. Such behaviour was named "dynamic strength effect".

In surrounding world this effect may occur when elastic waves produced by earthquake or charge detonation propagate across rock medium. If characteristics of wave enough to cause destruction than change of material state behind the front should be expected. Another example of dynamic rock strength is fracturing near free surfaces inside tunnels and mines due to spalling.

In laboratory conditions there are several techniques how to measure dynamic strength of rocks under different strain rates [1]. Servo-controlled and pneumatic machines are used to make measurement in relatively small speed range. For higher rates drop-weight machine or modified split Hopkinson pressure bar method are applicable. Extremely big velocities (up to 10^6 s^{-1}) are reached by spall or plane shock wave technique approach.

This work is dedicated to analysis of dynamic destruction tests published in [2, 3] of three types of rocks: Kimachi sandstone, Inada granite and Tage tuff. First material was investigated by two different methods - SHPB and spalling - to obtain dynamic tensile strength. Structural-temporal approach [4, 5, 6] have been chosen as damage criteria. According it every medium is characterized by additional material parameter - incubation time, describing its strength properties under dynamic conditions. Basing on experimental results range of incubation time variation for each rock type have been estimated. Curios dynamic effect of fracture delay when destruction occurs after phase of stress increasing in rupture plane is discussed.

2 LABORATORY STUDY OF DYNAMIC STRENGTH

Several experimental techniques are used to measure the dynamic strength of materials at present. The most popular is modified split Hopkinson pressure bar (SHPB) allowing to produce loading strain rates up to 10^4 s^{-1}. To get higher rates method of spall is required. A brief overview will be given here, for comprehensive description look [1, 7, 8].

2.1 Split Hopkinson pressure bar

Application of given technique extends classic compression and tensile strength tests to dynamic case. Sample of studying material is put between two metal bars (as demonstrated on fig.1) which dynamic and static mechanical properties well known. Stress impulse produced by striker inside incident bar propagates to bar-sample interface where partially reflects and partially passes through the test material into transmitted bar. Deformations of bars record by strain gauges and easily convert to stresses from both sides of sample. Typical curves of incident, reflected and transmitted signals have shown on fig.2(a).

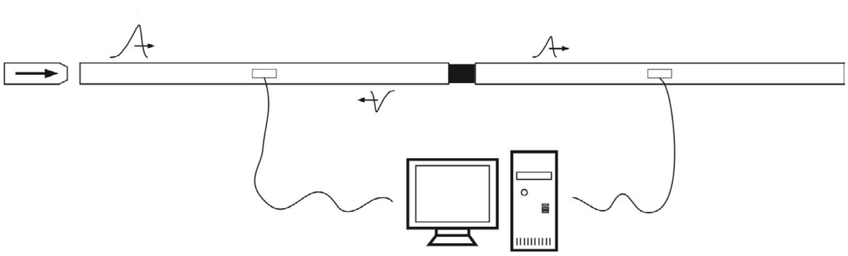
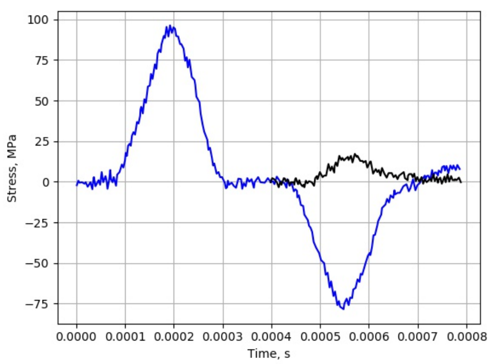
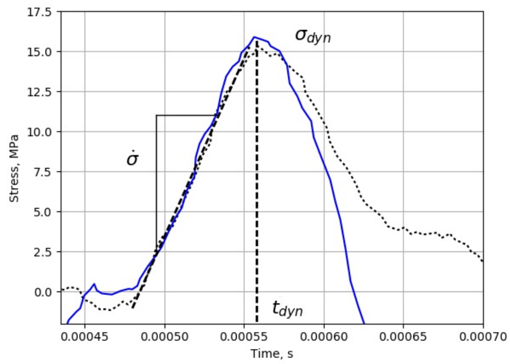


Figure 1: Scheme of split Hopkinson bar installation

Important part of experiment is to reach balance between different sides of sample (see fig.2(b)). If given condition is satisfied then the stress variation along investigated material can be neglected and quasistatic formulas may be used for measurement interpretation.



(a) Signals from incident and transmitted bars



(b) Stress balance

Figure 2: Stress curves obtained through experiment from [3]

In the cases of direct compression or tension test analysis of the loading history allows to determine: dynamic strength as a peak value reached through loading process, fracture time corresponding dynamic strength and stress rate as a slope of the tangent to the graph of the stress history. For indirect measurements stress curves from bars should be converted previously to internal stress at estimated point of destruction. In the case of Brazilian disc method such point corresponds to disc center, tensile stress σ_t here depends on external load σ by formula

$$\sigma_t(t) = \frac{2 \cdot \pi R^2}{\pi L D} \cdot \sigma(t) \tag{1}$$

where D - diameter of sample, L - its thickness and R is radius of metal bar. Easy to see that maximum tensile stress in the middle of disc will be calculated from peak value of external loading.

2.2 Spalling

Effect of spall appears when elastic wave propagates near the free boundary of material: compression wave reflects as tension wave and causes occurrence of cracks inside body. Although wave analysis can be quite complex laboratory conditions allow to consider one-dimensional problem.

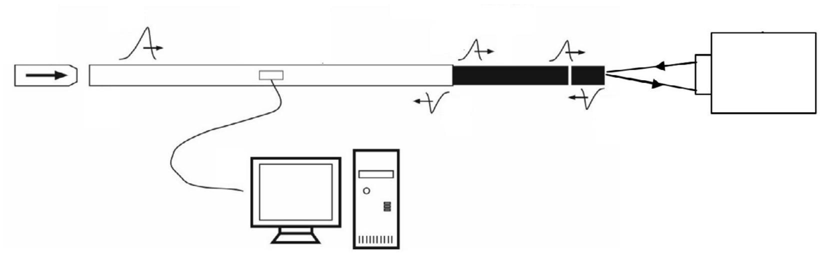
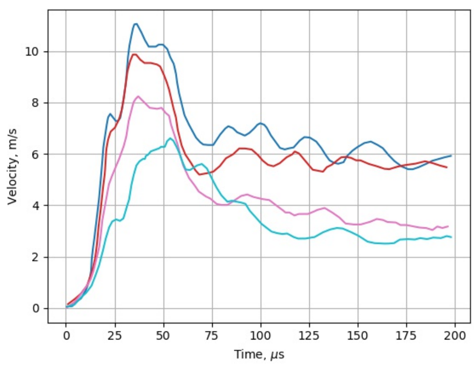
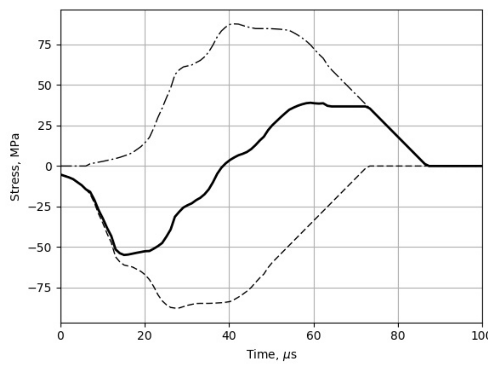


Figure 3: Scheme of spall experiment

For classical spall test extended cylindrical sample uses. Laboratory installation schematically shown on fig.3. Striker produces a stress impulse which propagates toward free end through studying material. Because of all materials significantly stronger in compression then tension damage arises when reflected impulse becomes dominant. Velocity of sample free end $U(t)$ is registered by laser interferometry (fig.4(a)).



(a) Free surface velocity profiles from [2]



(b) Stress history at some distance from free surface

Figure 4: Data from spall experiments

According to classical approach it "copies" acting compression stress profile $\sigma(t)$ and following formula is valid:

$$\sigma(t) = -\frac{1}{2}\rho c \cdot U(t). \tag{2}$$

The place and time of fracture appearing may be fixed independently. Stress history reconstruction (fig.4(b)) in crack plane may be done using (2):

$$\sigma(x,t) = \sigma(t - x/c) - \sigma(t + x/c) = \frac{1}{2}\rho c \cdot \Big(U(t - x/c) - U(t + x/c) \Big) \qquad (3)$$

here t is measured from the moment when stress impulse first came to free boundary, x - distance from free boundary. Obtained stress curve can be analyzed like in previous case of SHPB.

3 STRUCTURAL-TEMPORAL DAMAGE CRITERIA

Fracture formation in rocks, which lead to a partial or complete loss of material bearing capacity, occurs due to accumulation of damages at the micro level, fused with each other. Processes of growth and coalescence of micro destructions require some time to reach macro effect. By its nature ones close to relaxation process and may be characterized by temporal parameter reflecting the tendency of material to develop microdefects.

In Yu.V. Petrov and N.F. Morozov works have been introduced the notion of incubation time of material and proposed structural-temporal damage criteria based on this parameter. This concept has been successfully used for describing of dynamic strength phenomenon. Let $\sigma(x,t)$ be the stress function in point x inside elastic body subjected external loading. According incubation time criteria rupture of material in x at moment t will observe when following condition satisfied:

$$\frac{1}{\tau} \int\limits_{t-\tau}^{t} \frac{1}{d} \int\limits_{x-d}^{x} \left(\frac{\sigma(y,s)}{\sigma_{st}} \right)^{\alpha} dyds \geqslant 1. \qquad (4)$$

Where τ - incubation time of material, d - length parameter describing scale level and $\sigma_s t$ is static strength of material. Parameter α is dimensionless and characterizes reaction of medium on external stress impulse amplitude.

If external influence changes slowly enough, i.e. $\sigma \approx const$, then condition (4) reduces to well-known quasistatic one. At the same moment with rising strain rates time to fracture decreases to τ and even less. Pursuant to relation (4) amplitude of stress acting at given point should grow to cause damage as it is observed in experiments. So it may be said that incubation time controls strength behavior of material under dynamic conditions.

Analysis of experimental results to estimate incubation time of material requires a detailed reconstruction of elastic wave propagation through the sample. For stress impulses close to model, i.e. triangular or trapezoidal, theoretical relation based on condition (4) between dynamic strength σ_{dyn} observed in experiment and external impulse stress or strain rate ($\dot{\sigma}$ or $\dot{\varepsilon}$) (see [9, 10]). This curve depends on value of incubation time τ as on parameter and may be used to define parameter τ from comparison with measured data.

Samples for laboratory investigations are always limited in sizes. Most of them have dimensions from units to tens centimeters. All measured for such samples parameters should be related with this scale level.

Concept of structural-temporal damage criteria based on incubation time has been successfully applied to rock dynamic destruction problem understanding [11, 12].

4 INCUBATION TIME OF ROCKS

4.1 SHPB tests analysis

Brazilian method have been used to obtain tensile strength of three rocks in [3]. Laboratory setting consists of incident bar 2600 m in length and 1600 m transmitted bar. They diameters equal 37 mm. Incident stress impulse was produced by striker with length 200 mm and diameter 27 mm. Its approximate velocity was 7 m/s. Pulse shaper have been used to reach stress balance.

Tests samples have been made in the form of disc with diameter 50 mm and thickness $24-26$ mm. Mechanical properties of studying materials collected in table 1.

Table 1: Mechanical properties of rocks

Rock type	Density, g/cm^3	Compression, velocity, m/s	Young mod., GPa	St. tensile str., MPa	Total porosity
Kimachi sandstone	2.00	2710	6.5	4.82	17%
Inada granite	2.58	3950	56.8	7.3	0.5%
Tage tuff	1.76	2380	4.5	2.29	29%

For our work signal records from setting bars have been used. Incident and reflected impulses have been summed to get acting stress from the left side of the sample. After comparison with transmitted signal peak stress σ_p, corresponding time t_* and stress rate $\dot{\sigma}$ have been found for every dynamic test as was described in section 2. Then value of dynamic tensile strength σ^t_{dyn} have been calculated using peak stress and equation (1). Figures 2(a) and 2(b) demonstrate this procedure for Kimachi sandstone sample with number SB-1.

Series of high-rate measurements supplemented by static strength have been analysed to estimate incubation time for each rock type. Stress acting inside sample during experiment may well approximate by line function: $\sigma(t) \approx const \cdot t$. Such relation united with incubation time criteria (4) allows to obtain theoretical dependence of dynamic strength σ^t_{dyn} from stress rate $\dot{\sigma}$ [5]. Last one have been matched with experimental points to get value of τ.

Table 2: Interpretation of rock dynamic experiments

Rock type	Sample number	t_*, μs	$\dot{\sigma}$, GPa/s	σ_p, MPa	σ^t_{dyn}, MPa	τ, μs
Kimachi sandstone	SB-1	85	108	16.7	9.2	91
	SB-2	88	125	20.2	11.1	
Inada granite	GB-1	76	340	47.2	25.8	107
	GB-2	64	282	32.6	17.9	
Tage tuff	TB-1	94	81	13.9	7.6	150
	TB-2	93	74	12.6	6.9	

Theoretical curves based on structural-temporal approach (see fig. 5) approximate dynamic test results with accuracy 0.6 MPa for Kimachi sandstone, 3 MPa for Inada granite and 0.2 MPa for Tage tuff.

4.2 Spall tests analysis

Kimachi sandstone. Spall test is different from previous case where whole sample is always destroyed after experiment. Due to extended size of sample for spalling fracture plane may occur in various point along the length of the rod depending on produced wave parameters. Sometimes several consecutive cracks are formed dividing the original sample into fragments. So fracture position is additional experiment parameter which should be taken into account for correct results interpretation.

Main data measured in spall test is free surface velocity (see fig. 4(a)) which helps to reconstruct stress impulse produced in experiment and to get some additional information. Whole curve may

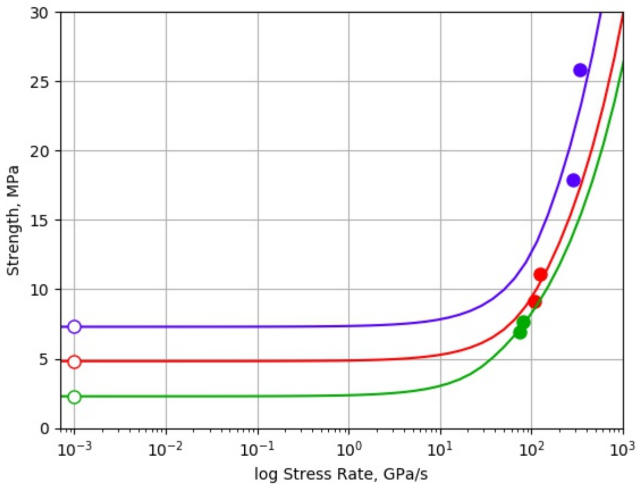


Figure 5: Incubation time curve and experimental data for: Kimachi sanstone (red), Inada granite (blue), Tage tuff(green)

be divided into two parts: trapezoid-like before fracture and oscillations after [7, 8]. First one uses to calculate stress history during experiment and last one to specify the time of destruction. Because of fracture occurred some impulse turns out to be locked in breakaway fragment and circulates between two surfaces which causes oscillations. Its period uses to estimate fracture time.

Author of [2] made several spall tests with Kimachi sandstone samples 60 mm in diameter and 300 mm in length using underwater shock waves. For every type of loading parameters typical free surface velocity and variation of fracture position have been measured. This data together with incubation time criterion is analysed in present work to estimate parameters of dynamic destruction of given rock.

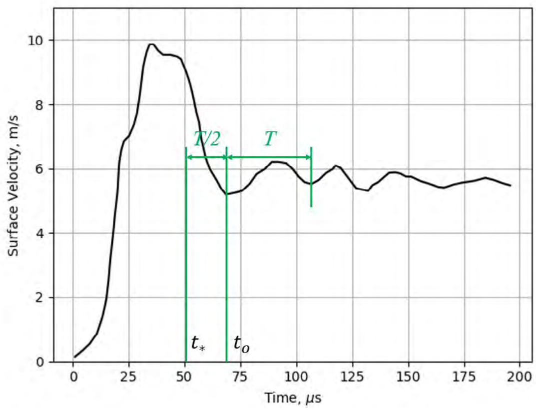
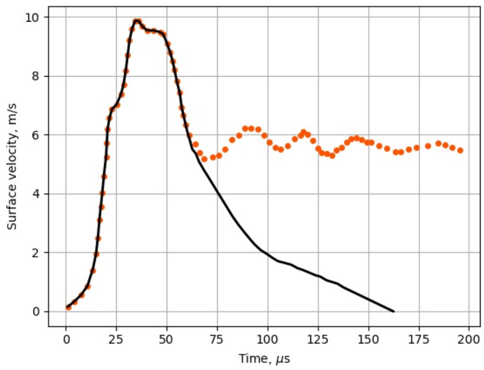


Figure 6: Example of temporal characteristics estimation from test results

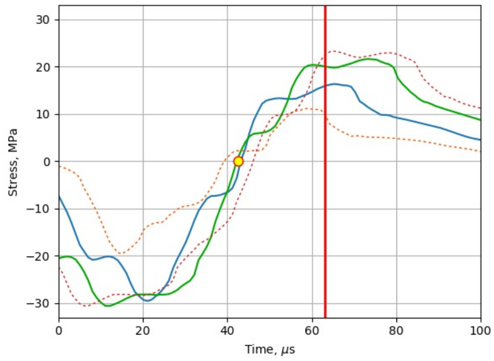
Table 3: Spall fracture parameters

Charge lenght	t_o, μs	T, μs	t_*, μs	x, cm
50	72.8	19.3	63.2	4-6.5
70	68.7	38.1	49.6	4.5-6
100	81.5	37.5	62.8	5-8
200	119.6	39.6	99.8	9-11

First minimal value on surface velocity after rapid drop reflects fracture initiation and fact that wave produced in that process has reached free border. Corresponding time is marked for t_o. Then this wave goes through sample fragment from free surface to fracture and back that causes fluctuations in the velocity of the free surface. Period of such oscillations T is equal to double time of wave propagation from fracture to surface. Values of t_o and T are used to get moment t_* when spall fracture occurs. Obtained temporal parameters accompanied with fracture location data from [2] for different loading conditions are contained it the table 3.



(a) Surface velocity profile reconstruction



(b) Stress history at different cross sections

Figure 7: Stress analysis of spall experimental data

To determine magnitude and rate characteristics of stress acting in fracture plane recorded curve should be corrected. In considered case initial impulse continues with a "tail" as on fig. 7(a). Stress curve have been calculated by (2). Negative sign corresponds to compression.

Comparison of stress histories for different cross sections with fracture data shown on fig. 7(b). Case of 50 mm charge length is presented here. Blue and green solid curves describe stress behaviour in sections 4 and 6.5 cm from free end correspondingly, yellow point marks the occurrence of extension, red vertical line is fracture time indicator. Dotted orange and purple lines show stresses in sections 2 and 8 cm. According to experimental results crack arises at any point of the interval $4 - 6.5$ cm equally likely, and stress calculation demonstrates that destruction has come after intensive stress raising when load kept almost constant.

Fig. 7(b) demonstrates the difference in stress histories along laboratory sample: tensile forces arise earlier near the free end, but their magnitude as bigger as they are farther from the edge until it reach the amplitude of the shock pulse. It is also curious that, according to the calculations, destruction in this case occurs after the phase of stress growth when the load in fracture plane is kept at approximately the same level. Such effect is inconsistent with quasistatic representations of failure at a given stress threshold and requires analysis using the dynamic strength criterion.

According to structural temporal approach effect of fracture delay may be considered if amplitude of trapezoid load impulse quite close to value of limiting stress that material is able to withstand at given dynamic conditions. Easy to see that increasing of loading amplitude with constant stress rate will cause the shift of crack plane toward free surface. It follows from relation (4) that signal close to limit value will lead to the situation when integral corresponding some cross section will accumulate due to the stress "shelf". This effect can be measured accurately if every dynamic destruction test will be accompanied by independent fracture location and time measurements.

Because of uncertainty in rupture plane it is not possible to specify the exact value of the incubation time for Kimachi sandstone. Variation of parameter τ in (4) have shown that any value from $55 - 70$ μs can be taken as given material characteristic. Static strength was assumed to be 3.7 MPa according to [2].

5 CONCLUSIONS

Dynamic rock stability behaviour may be successfully described by structural-temporal approach based on incubation time notion. Last one is effective tool for assessing material strength under high-speed loads.

Incubation time τ for three types of rock have been obtained using SHPB experiment results. These values are 91 μs for Kimachi sandstone, 107 μs for Inada granite and 150 μs for Tage tuff.

Spall test analysis have shown interesting dynamic effect of fracture delay. Experimental observation of given effect is related with accurate analysis of destruction time and stress curve acting in crack cross section. Temporal characteristic τ obtained through spall tests for Kimachi sandstone is less than obtained previously. It may be caused by different stone properties as indicated by static strength.

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